Los Alamos

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memorandum

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FROM Don Brown

MAIL STOP/TELEPHONE J-978/7-1914

SYMBOL ESS-4/82/218

SUBJECT EE-2 FRACTURE INITIATION BY SIMULTANEOUS WELLBORE COOLING AND PRESSURIZATION

Introduction

One of the more significant -- though generally unrecognized -- technical achievements of the HDR program has been the demonstration of multiple fracture initiation by simultaneous wellbore cooling and pressurization. This technique, if applied to the Phase II reservoir, would undoubtedly result in the formation of numerous incipient fractures along the entire EE-2 openhole section. This simple and straightforward method of developing a multiply-fractured HDR reservoir could have a profound influence on the cost of reservoir development, and the economics of the HDR concept in general.

It is appropriate to remember that besides the HDR concept itself, Los Alamos developed the concept of openhole fracturing using inflatable packers, directional drilling in hot igneous rock, and downhole seismic fracture detection; to name only some of the areas where we have proceeded the petroleum industry in developing <u>new</u> techniques to be applied to the often significantly different geothermal situation.

Past Results

It is the unanimous conclusion of those of us who have studied the Phase I reservoir in detail,* that we have opened numerous fractures -- or pre-existing joints -- along the lower part of the EE-1 wellbore, by simultaneous cooling and pressurization. Over the 2600 foot wellbore interval from 7000 feet to 9600 feet -- about 220 feet horizontally -- there are at least 14 distinct fractures which have accepted flow, as indicated

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*Lee Aamodt, Don Brown, Hank Fisher, Hugh Murphy, and Bob Potter by temperature depressions measured along the wellbore. Figure 1 shows one such temperature survey: the mostly-recovered EE-1 temperature profile measured 49 days after the end of Run Segment 2 (the 75-day flow test).

To respond to potential questions concerning time and cooling, Figs. 2 and 3 show the corresponding EE-1 temperature profiles measured approximately one and two years earlier. The partially-recovered EE-1 temperature profile shown in Fig. 2 was measured 36 days following the 10 bbl/min 155,000 gallon injection of Expt. 161. The object of this phase of Expt. 161 was to extend an EE-1 fracture to intersect GT-2A, or if already connected, to reduce the pre-existing fracture system flow impedance.* As can be seen in Fig. 2, we aparently activated a multiple fracture system in EE-1, with flow about evenly distributed between four fractures (4, 5, 6, and 7) intersecting along about 500 feet of the wellbore. Connections 2 and 3 also appear to have accepted considerable flow considering their relative cooling: about half that of connections 4 through 7.

Prior to the temperature survey of 7/27/76 shown in Fig. 3, we had pumped a total of almost 500,000 gallons into EE-1 over a period of about 6 months. However, the most severe thermal stressing of the wellbore probably resulted from the first extended 5 bbl/min injection, which occured during Expt. 120.# At the end of this 14-1/2-hour pumping interval, the rock temperature 4-1/2 inches from the wellbore surface would have been cooled by about 70°C, corresponding to an induced tensile thermal stress of 5400 psi. This induced stress would have been sufficient to overcome the maximum wellbore stress concentration -- in the S_2-opening direction -- of 4000 psi above the wellbore pressurization level, with sufficient residual tensile stress to open all of the calcite-sealed S_2 joints intersecting the openhole wellbore below about 7000 feet. The calculated radial temperature gradient out from the wellbore after 14-1/2 hours of coolant flow at 5 bbl/min is

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*See Ref. 1, "GT-2A Pumping Tests: A Lesson in History," Memorandum G-3/78/#34.

183,000 gallons injected into EE-1 in 14-1/2 hours, at a surface pumping pressure of about 1350 psi.

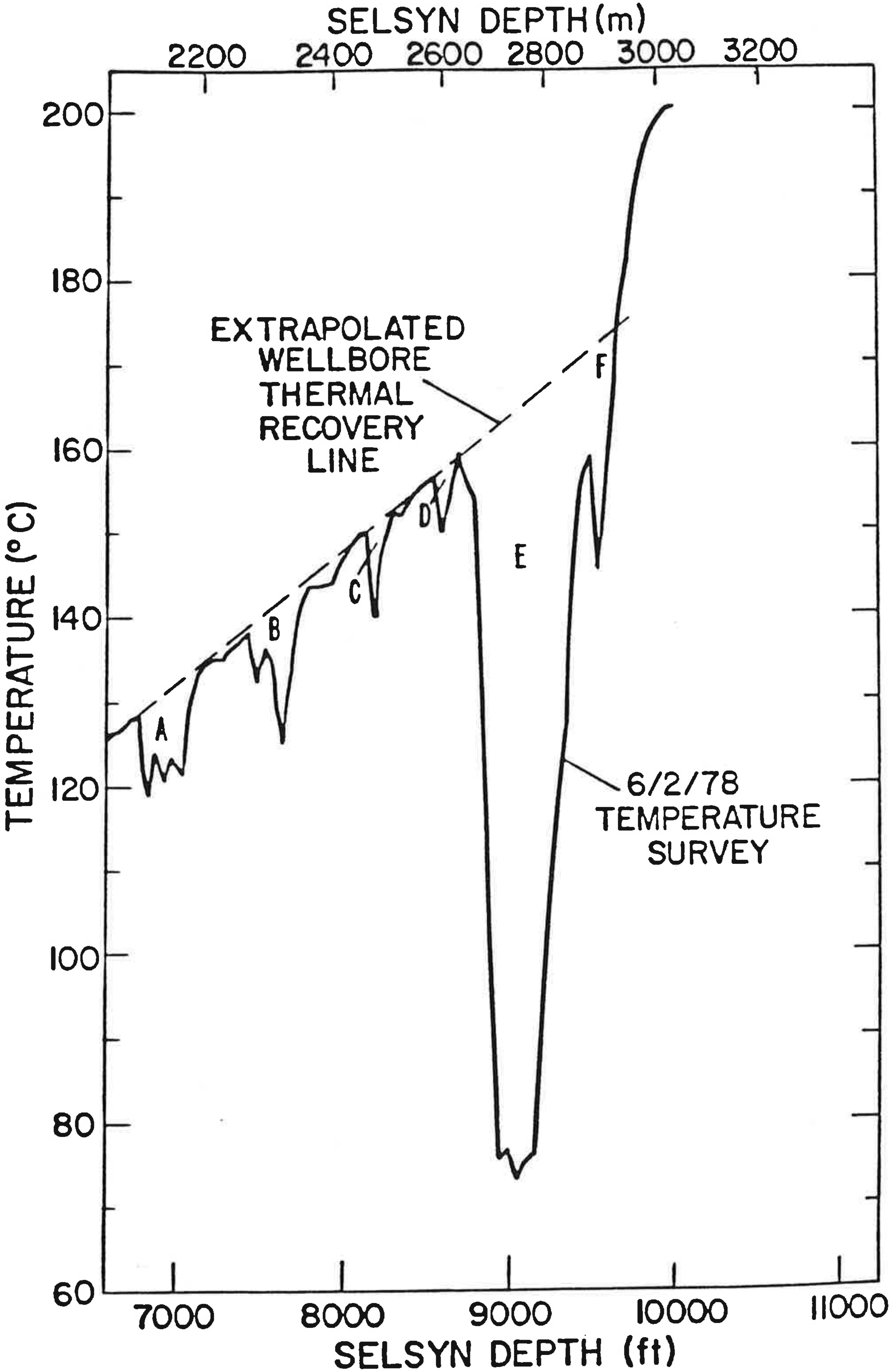
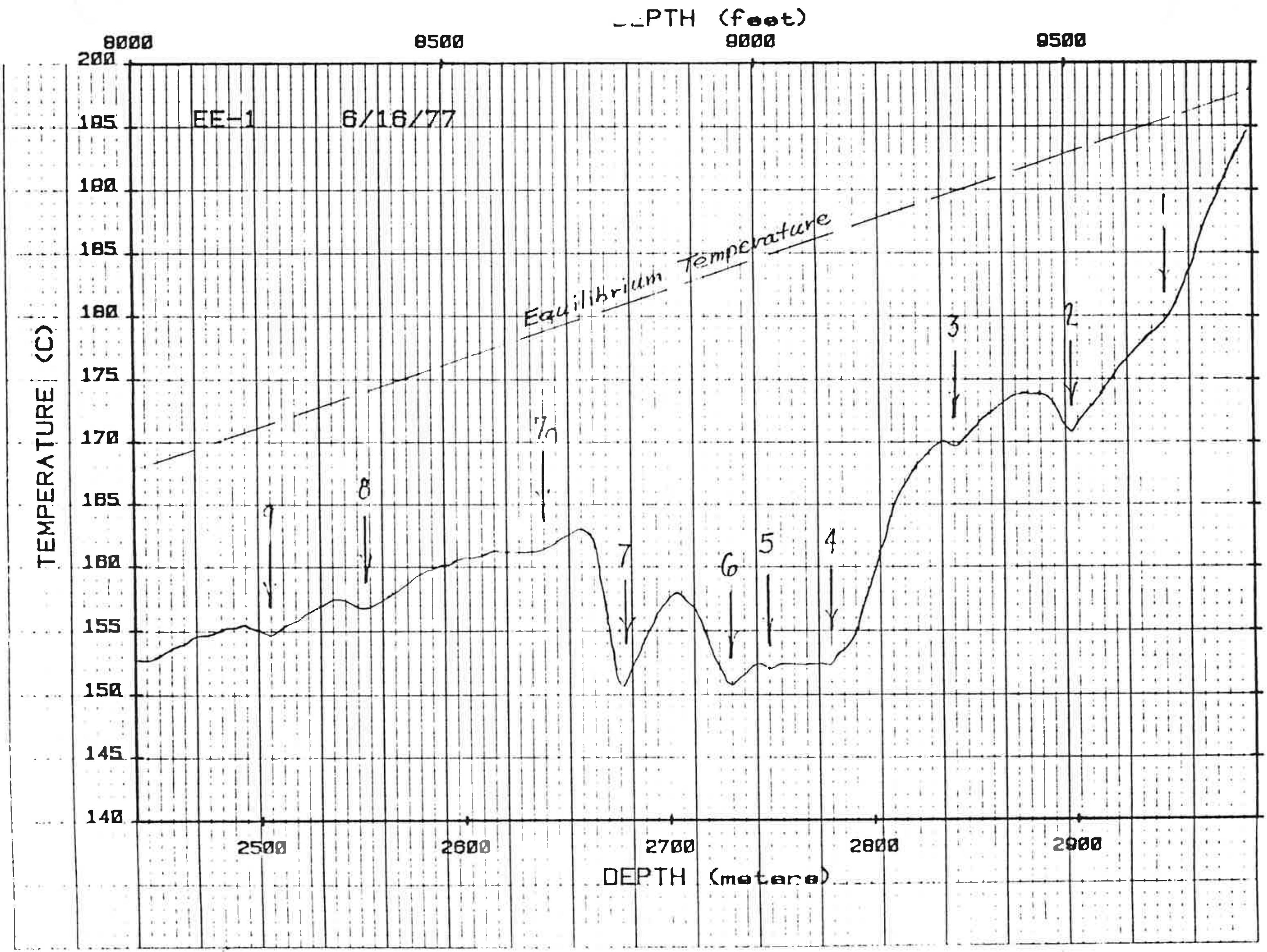

SELSYN DEPTH (m)
2200
2400
2600
2800
3000
3200
200
180
160
140
120
100
80
60
TEMPERATURE (°C)
EXTRAPOLATED WELLBORE THERMAL RECOVERY LINE
A
B
C
D
E
F
6/2/78 TEMPERATURE SURVEY
7000
8000
9000
10000
11000
SELSYN DEPTH (ft)

Figure 1



DEPTH (feet)
8000
8500
9000
9500
EE-1
6/16/77
Equilibrium Temperature
TEMPERATURE (C)
200
185
180
185
180
175
170
165
160
155
150
145
140
1
2
3
4
5
6
7
7a
8
2500
2600
2700
2800
2900
DEPTH (meters)

Figure 2

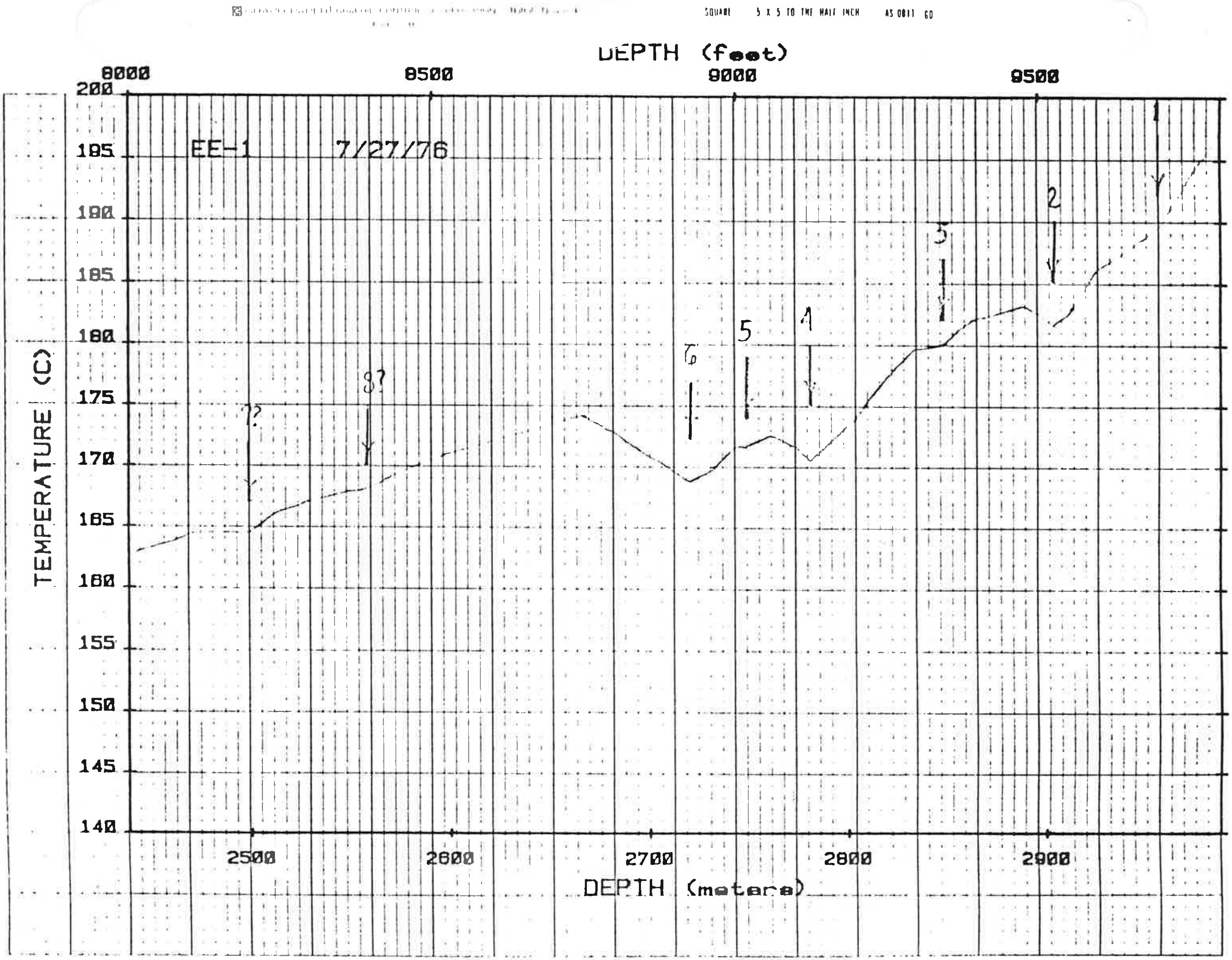

SQUARE 5 X 5 TO THE HALF INCH AS 0811 60
DEPTH (feet)
8000
8500
9000
9500
EE-1
7/27/76
200
195
190
185
180
175
170
165
160
155
150
145
140
TEMPERATURE (C)
1
2
3
4
5
6
7?
8?
2500
2600
2700
2800
2900
DEPTH (meters)

Figure 3

shown in Fig. 4. This radial gradient, for a mean EE-1 wellbore depth of 2500 m (8200 feet) was calculated by Zora Dash using George Zyvoloski's flow-test-confirmed Wellbore Heat Transfer Code.

Once the S_2 joints had opened along the EE-1 wellbore during Expt. 120, the induced thermal stress would have been sufficient to extend these open joints, at a surface pressure of 1350 psi, to a depth where the formation cooling was at least 11°C. From Fig. 4, this radial fracture penetration would have extended about 18-1/2 inches out from the wellbore. Natural permeation along these joints would have then taken over.

It is this author's opinion, based on an extensive analysis of past flow experiments in the Phase I reservoir, that all the fracture connections indicated in Fig. 1, exclusive of the four connections that comprise entrance E, represent cooling from flow through S_2 joints. Due primarily to the extremely low (less than 0.5 psi/gpm) fracture flow impedance obtained during Run Segment 3,* it is apparent that the fracture connections representing entrance E in Fig. 1 are a parallel set of S_3 joints. This conclusion is supported by the initially reduced heat transfer area at the beginning of Run Segment 3, shown in Fig. 11 of Ref. 2, in combination with the significant change in the outlet flow distribution in GT-2B between low and high back pressure flow conditions.

It should be remembered that flow entrance F in Fig. 1 was the primary EE-1 fracture entrance during Run Segments 4 and 5, subsequent to cementing off the annular entrance to all higher (behind the casing) fracture connections. It was stated in the Run Segment 5 report (Ref. 3) that "... flow in the lower part of the reservoir is governed by a higher (component of in-situ) stress than the earlier reservoir." The EE-1 injection flow/pressure data support this conclusion. At the same EE-1 injection flow rate of 10 bbl/min, and after the same amount of injected fluid (150,000 gals),

*Expt. 186, the 28-day high back pressure flow experiment.

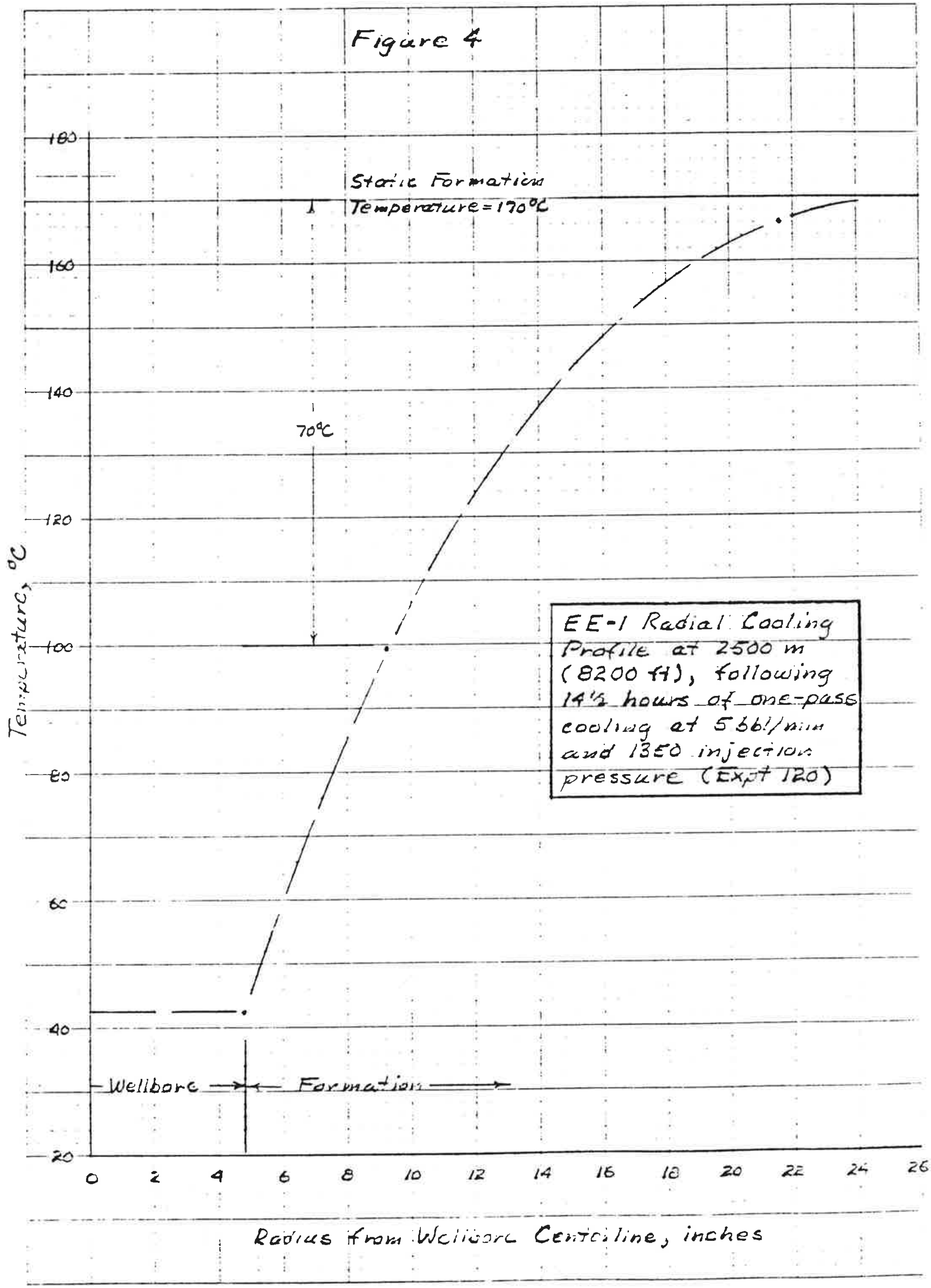


Figure 4
Static Formation
Temperature = 170°C
70°C
EE-1 Radial Cooling Profile at 2500 m (8200 ft), following 14½ hours of one-pass cooling at 5 bbl/min and 1350 injection pressure (Expt 120)
Temperature, °C
180
160
140
120
100
80
60
40
20
Wellbore
Formation
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Radius from Wellbore Centerline, inches

entrance F at 9620 feet required a surface pumping pressure of 2730 psi,* while entrance E at 9050 feet required only 1880 psi,# for a net difference of 850 psi in less than 600 feet. From this and other data, the difference between the two horizontal earth stresses (S_2 and S_3) in the Phase I reservoir is estimated to be about 900 psi. In Fig. 5, most of our previous earth stress determinations are plotted, along with the inferred gradients of S_2 and S_3. Most of these earth stress values were determined by injection pumping tests, or during extended through-flow heat extraction experiments.

One obvious question arises: How did we manage to open so many S_2 joints, but so few S_3 joints, along the EE-1 wellbore below 7000 feet? By examining the plan view of the EE-1 drilling trajectory shown in Fig. 6, one reasonable answer is apparent. From 7225 feet to 9685 feet, EE-1 was drilled in a southerly direction, essentially perpendicular to the accepted direction for the least principal earth stress (S_3), and therefore roughly parallel to the second earth stress (S_2). Therefore, the horizontal exposure to S_3 joints (joints opening against S_3) was no more than about 40 feet, while the corresponding exposure to S_2 joints -- oriented roughly E-W -- was over 200 feet.

Phase II Reservoir

In contrast to the Phase I reservoir situation, hole EE-2 was drilled in a more-or-less eastwardly direction, and thus roughly perpendicular to EE-1. Figure 7 shows a plan view of the drilling trajectory of EE-2 over the lower openhole section (below ~ 11,500 feet).

From our previous -- and extensive -- experience in the Phase I reservoir, it is anticipated that numerous S_3 joints (oriented roughly N-S) intersect the EE-2 openhole section below the casing. However, from the results of Expt. 2003, all of these joints presently appear to be tighly sealed near the wellbore, possibly by "black gunk" and/or cuttings.

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*Expt. 203 on 3/14/79, the initial post-cementing MHF fracture extension experiment.

#Expt. 161 on 5/11/77, discussed previously.

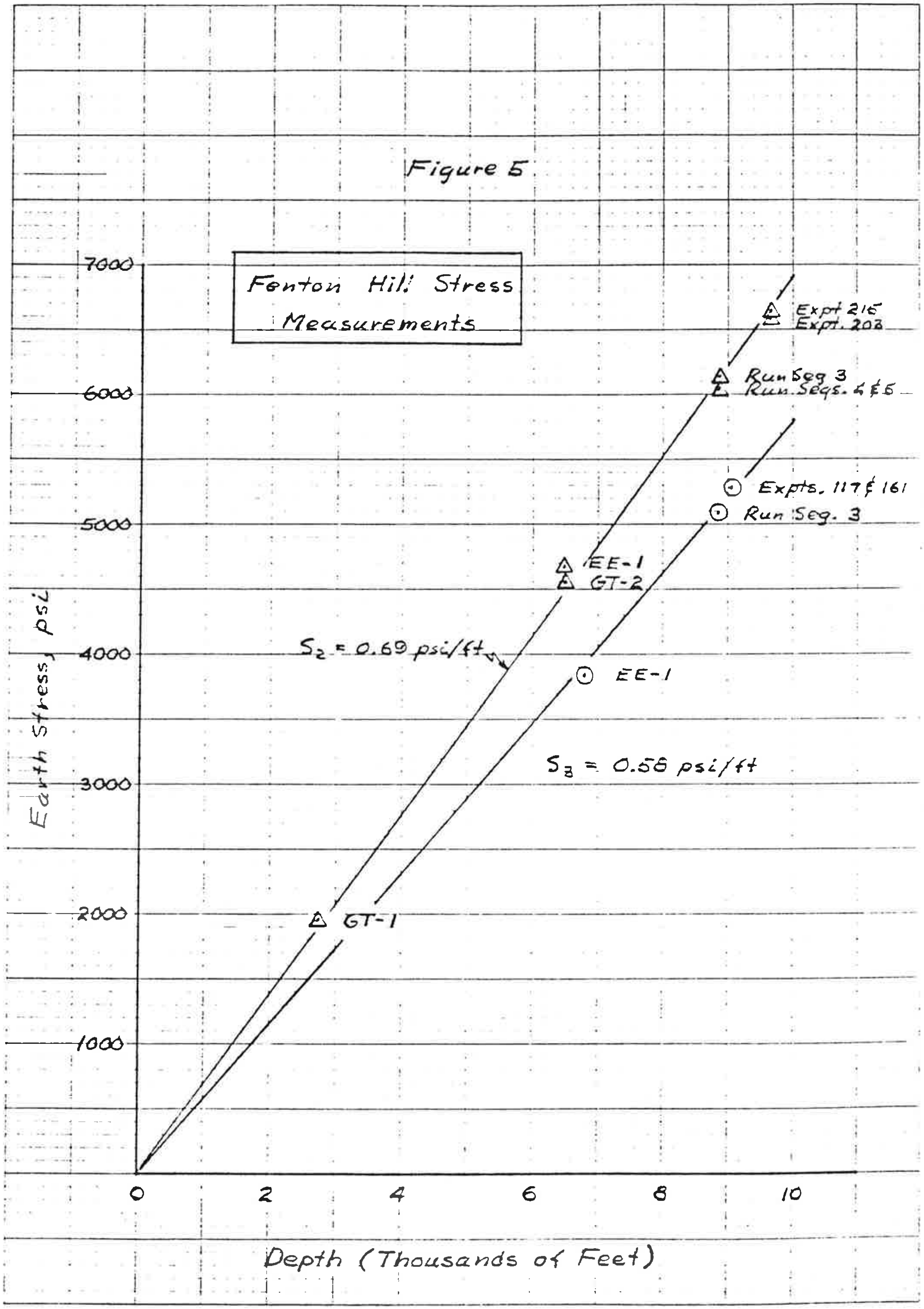
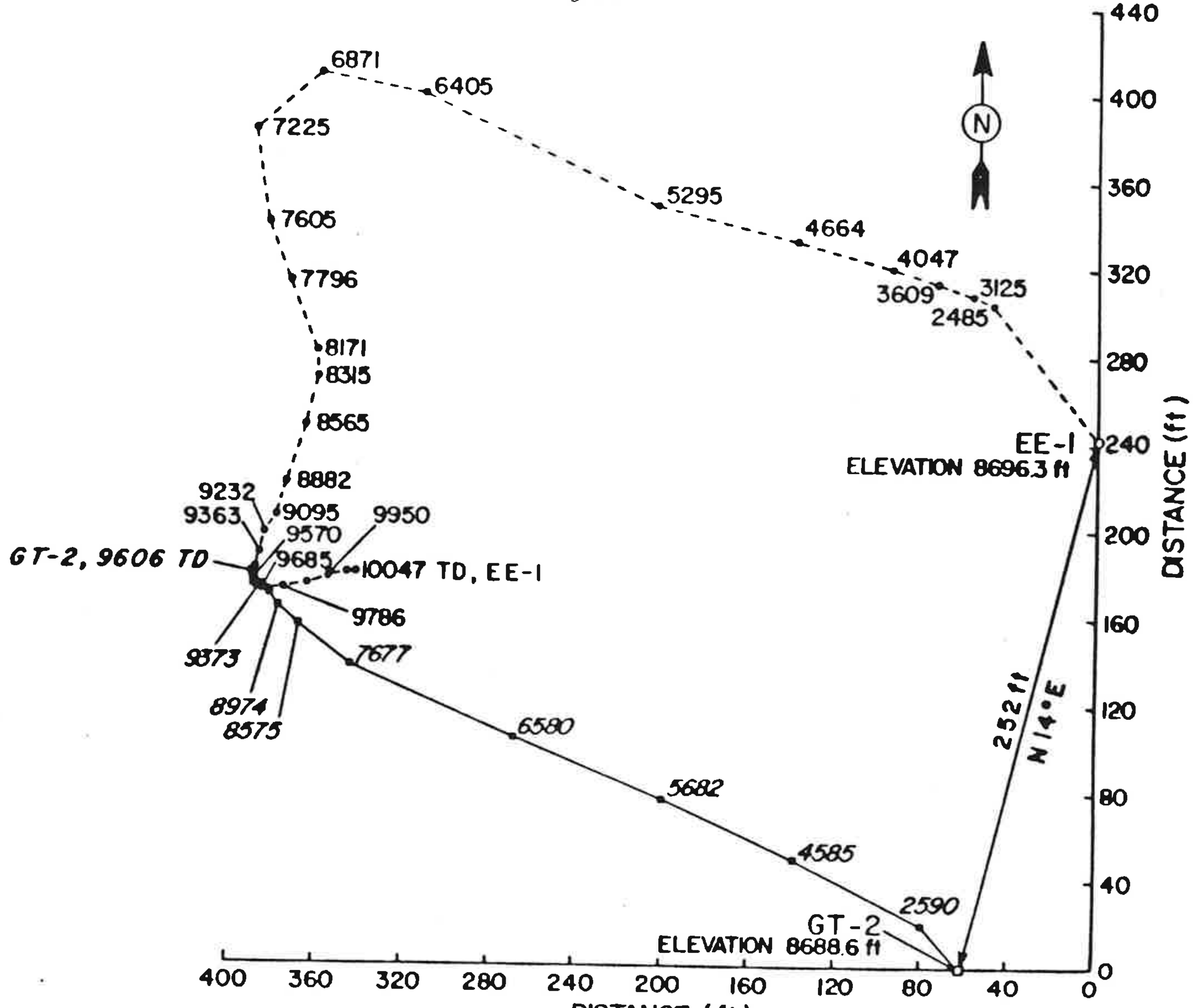


Figure 5
Fenton Hill Stress Measurements
Expt 215
Expt. 203
Run Seg 3
Run Segs. 4 & 5
Expts. 117 & 161
Run Seg. 3
EE-1
GT-2
S_2 = 0.69 psi/ft
EE-1
S_3 = 0.56 psi/ft
GT-1
Earth Stress, psi
7000
6000
5000
4000
3000
2000
1000
0
2
4
6
8
10
Depth (Thousands of Feet)

Figure 6



DIRECTIONAL DRILLING IN GT-2 AND EE-1, PLAN VIEW
(DEPTHS, IN ft, MEASURED FROM ELEVATION TAKEN AT CASING FLANGE NEAR GROUND LEVEL)

In contrast to EE-1, the horizontal exposure to E-W oriented S_2 joints is relatively limited in EE-2. Therefore the probably more numerous S_3 joints intersecting EE-2, with their higher flow potential at any given wellbore pressurization level, should dominate the Phase II reservoir. Any S_2 joints that happen to be activated should be severely flow restricted relative to the S_3 joints, due to the additional 900 psi closure stress in the N-S direction.

Reversing the Near-Wellbore Earth Stress Gradient by Cooling

By counterflow cooling,* the earth stress gradient out at least 20 inches from the wellbore can be effectively reversed. This is obvious when one considers that after a few hours of flow, the fluid temperature gradient in the annulus is much less than the surrounding earth temperature gradient. As a consequence, the formation cooling, and therefore the thermally-induced tensile stress, increases with depth. This cooling effect is shown graphically in Fig. 8. Over the 3700-foot interval below the casing in EE-2, the cooling ΔT at a point 16-3/4-inches out from the wellbore almost doubles from top to bottom after 4 days of counterflow cooling.

With a cold column of fluid in EE-2, the effective fracturing pressure against S_3 increases by only about 450 psi over this same EE-2 openhole interval.# For rock with a Young's modulus of 400 Kb, a Poisson's ratio of 0.25, and a linear coefficient of thermal expansion of $10^{-5}/^{\circ}C$,

$$\Delta\sigma_{th} \sim 77 \times \Delta T \quad \text{(in psi)}$$

Figure 8 shows a 20.8°C difference in formation cooling from the top to the bottom of the EE-2 openhole section, at a radial location 16-3/4-inches away from the wellbore surface. This induced near-field thermal stress gradient in the vertical direction overcompensates for the earth stress gradient by almost a factor of 4.

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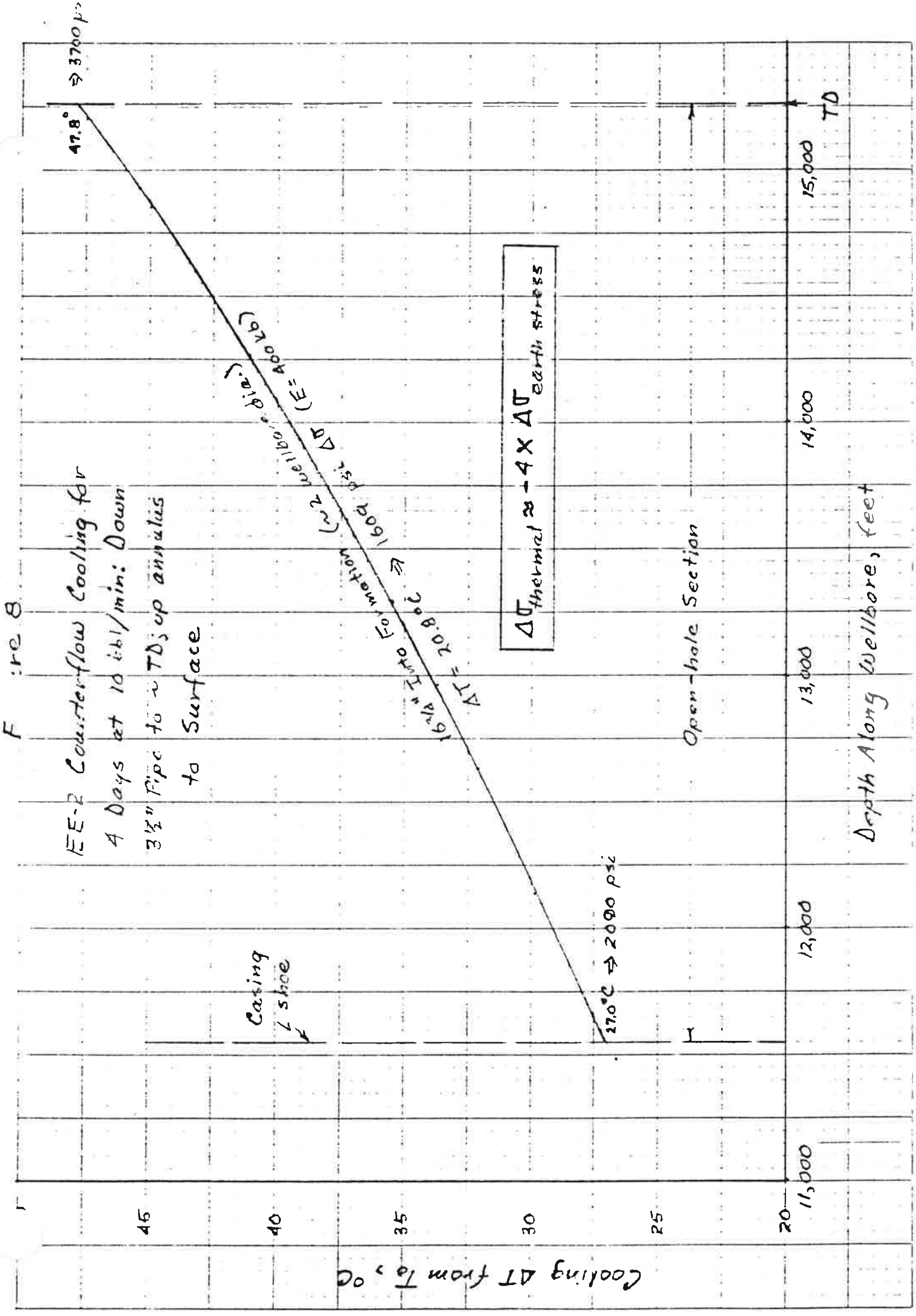
*Flow down 3-1/2-inch drill pipe, and back up the annulus to the surface. The workover rig pumps should be capable of circulating EE-2 to TD at about 10 bbl/min.

#The S_3 gradient (from Fig. 5) of 0.58 psi/ft minus the fluid gradient of 0.43 psi/ft times the TVD interval of 3080 feet.


F ;re 8
EE-2 Counterflow Cooling for 4 Days at 10 bbl/min: Down 3½" Pipe to ≈ TD; up annulus to Surface
47.8° ⇒ 3700 psi
TD
16" Into Formation (~2 wellbore dia.) ΔT = 20.8°C ⇒ 1600 psi Δσ (E= 400 kb)
$\Delta\sigma_{thermal} \approx 4 \times \Delta\sigma_{earth\ stress}$
Open-hole Section
Casing shoe
27.0°C ⇒ 2000 psi
11,000
12,000
13,000
14,000
15,000
Depth Along Wellbore, feet
20
25
30
35
40
45
Cooling ΔT from To, °C

Therefore, following a 4-day pre-cooling period, there exists a strong potential for initiating hydraulic fractures preferentially near the bottom of EE-2 during wellbore pressurization. If, however, EE-2 is allowed to thermally recover prior to pressurization, incipient sites for fracture initiation will still be present in the form of thermal stress cracks, and will be concentrated near the bottom of the hole. These thermal cracks will have broached all the way through the wellbore "stress cage," that cylindrical region surrounding the wellbore which is under abnormally high compressive stress due to the presence of the hole,* significantly reducing the wellbore breakdown pressure.

Proposed EE-2 Multi-Fractured Reservoir Development Plan

The reservoir development program herein proposed has the general advantage --ultilizing simple and modest-priced hardware -- of opening and then flow testing a number of EE-2 fracture connections over the lower one-third of the open-hole section (say on the order of 10 to 20), and then subsequently reservoir-drawdown-testing only two or three of these connections -- if desired. The plan fits within the general framework of Pettitt's most recent revision,** but is much more success oriented. This proposed plan, however, emphasizes the use of Lynes inflatable packers ahead of the Guiberson packers, due primarily to the author's extensive field experience with Lynes packers, coupled with a recognition of their much longer wellbore sealing length vis a vis the Guiberson packers. Having planned and supervised the successful running, setting and cementing of both liner/PBR assemblies in GT-2, as well as all of the Lynes packer tests in GT-2 and EE-1, it is my experienced opinion that the Lynes packers have a much better chance of success in EE-2 than the cemented-in liner/PBR assembly. This echos the consensus opinion of the recently-convened industry panel,# that we should exhaust all of our packer options -- in

*At two diameters (17-1/2-inches) away from the wellbore wall, this stress concentration is only about 4% above the far-field stress level.

**"Plan for Development of EE-2/EE-3 Multiple Fracture System," Revision No. 7, 2-25-82.

#HDR Geothermal Fracturing Workshop, 3-3-82.

non-straddle configurations -- before resorting to the cemented-in liner/ PBR approach.

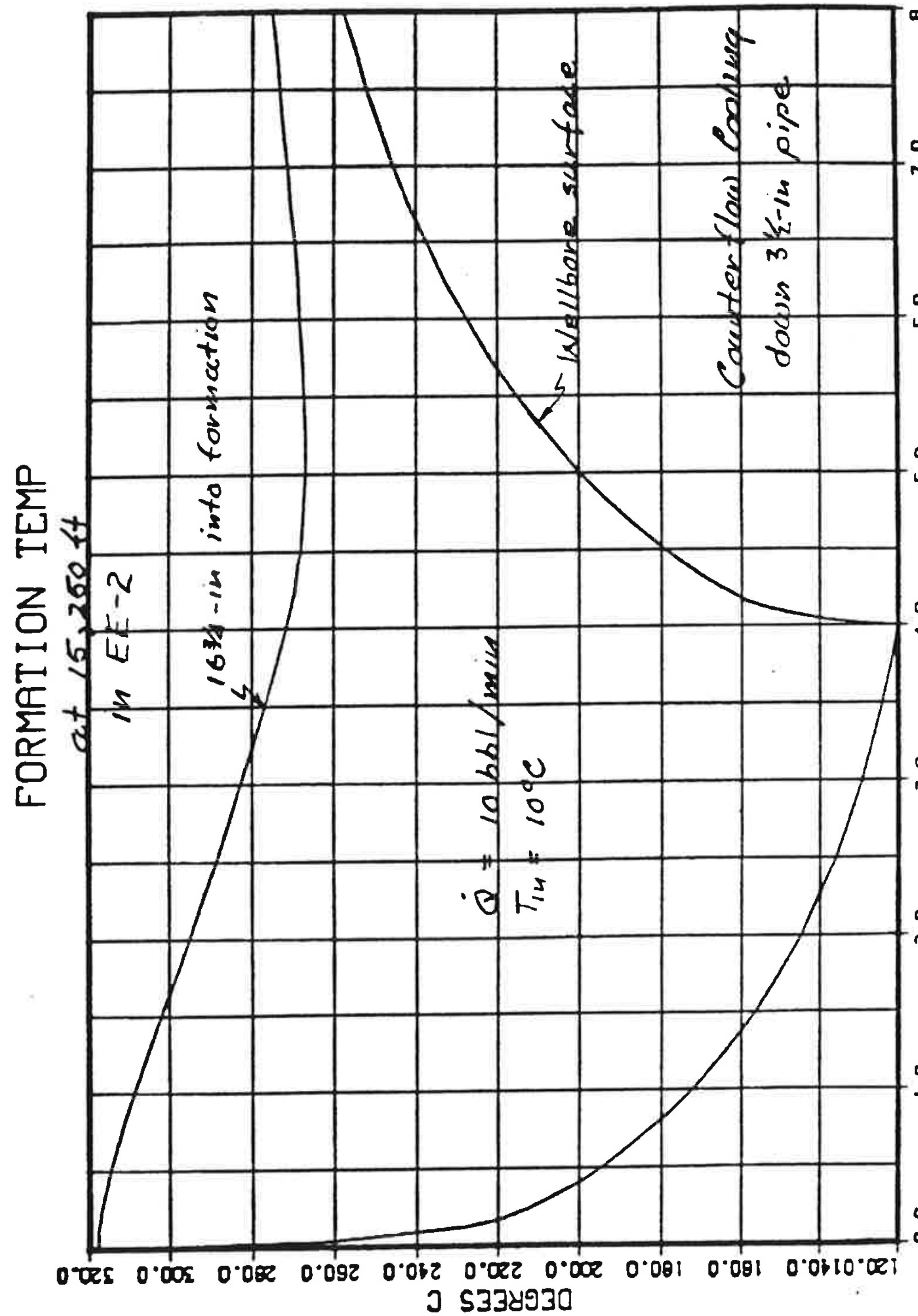
However, this proposed plan delays both the cement testing and explosive fracture initiation experiments until both the Lynes and Guiberson packers have at least been initially tested -- in the hope of saving both considerable time and money if the packers are successful. The plan is as follows, assuming that the logging cable has previously been cleared from EE-2, and the hole has been rabbited and then washed/redrilled to bottom:*

1. Run in to TD with 3-1/2 drill pipe.
2. Cool the hole by counterflow circulation at ~ 10 bbl/min for a period of 4 days. This cooling will accomplish two things:
   (a) Sufficiently cool the hole so that there is at least a 4-day period to trip out with the drill pipe, log as necessary, and then slowly run in with a Lynes packer assembly, and yet not exceed a bottomhole recovered temperature of 275°C.
   (b) Create insipient fractures preferentially near the bottom of the hole.

   Figure 9 shows the EE-2 bottomhole temperature profiles (wellbore surface and 16-3/4-inches into the formation) for 4 days of counterflow cooling at 10 bbl/min followed by 4 days of temperature recovery. As is shown, the recovered bottomhole wellbore temperature after 4 days is only 257°C, still below the Lynes packer proof test temperature of 275°C for 72 hours in casing, with a 5000 psi pressure drop across the element.
3. If required, run a commercial gamma log through the drill pipe, and then trip out.
4. Make up the Lynes packer assembly, run in the hole (slowly) and set 300 feet off bottom.
5. Open the packer to the lower packed-off interval, and slowly ramp up the pressure (with the large Kobe pump at 34 gpm) to fracture breakdown at or near 3000 psi. While the packed-off region is

*Steps A1-A4 of Pettitt's plan, pp. 3-4.

Figure 9



FORMATION TEMP
at 15,250 ft
in EE-2
16¾-in into formation
Wellbore surface
Counter-flow Cooling
down 3½-in pipe
Q̇ = 10 bbl/min
T_in = 10°C
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
DAYS
120.0
140.0
160.0
180.0
200.0
220.0
240.0
260.0
280.0
300.0
320.0
DEGREES C

being pressurized, the pipe rams should be closed and the annulus pressurized with the small Kobe pump at a pressure lagging the large Kobe by 200-300 psi, to minimize the ΔP across the packer. (The annulus pressure should not be allowed to exceed 1200 psi, however).

6. After formation breakdown, vent and then repump as above to determine S_3.
7. If successful, call out Dowell for high volume pumping if not attainable with the rig pumps,* rig up the wellhead flow manifold, and continue Kobe pressure testing. Then extend the fracture(s) to EE-3 at 10 bbl/min and evaluate the flow connections.

8a. If the Lynes packer failed, or was only partially successful, repeat steps 4 through 6 at least several additional times.# If still unsuccessful, switch to the Guiberson packer (non-straddle configuration).

8b. Run in the Guiberson packer on drill pipe (with a tail pipe), and repeat steps 4 through 8a (Guiberson = Lynes).

9. If either the Lynes or Guiberson packers are successful through Step 7, trip out with the packer, trip in with drill pipe to 300 feet off bottom, and temperature-log the bottom 300 feet of the open hole to determine the number of fracture entrances.
10. Re-run the successful packer to a position 1000 feet off bottom and repeat Step 7 above to chill and open the entire packed-off region; then temperature log the bottom 1000 feet as in Step 9 above, to determine the new fracture entrances.

11a. If all packers have failed after repeated attempts (most unlikely), and after rabbiting the hole, use explosive fracture initiation to open up the bottom of EE-2.

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*<u>All</u> of our Phase I fracture connections were made at injection flow rates at or below 10 bbl/min.

#One of the additional advantages of the Lynes packer is that with one simple modification, the packer element can be deflated in such a way that pressure can then be applied from <u>below</u> the packer, collapsing the packer element and literally pumping the packer up the hole -- assuming almost fail-safe retrieval.

(a) Test the openhole section with the Kobe pump. If successful:

(b) Set a casing packer (high-temperature Baker) just above the casing shoe; then pressurize and cool the entire openhole section while pumping out the bottom, initially using the rig pumps if possible.

(c) Evaluate the fracture connections by flow tests and logging as appropriate.

(d) If unsuccessful in (a) above, repeat Step 11a.

11b. If all else fails, proceed with the Liner/PBR assembly as per Pettitt's plan.

A Closing Comment

It should be pointed out that after an initial fracture is produced -- by any means available -- at the bottom of EE-2 and then extended to EE-3 with the injection of at least a million gallons of cold water, the entire open-hole section of EE-2 will have been severely cooled and thermal stress cracked. Thus, following this initial fracture extension test, the EE-2 open-hole wellbore will be in an extensively thermally cracked condition . . . so we need to learn to cope with this situation eventually, if it presents a problem.

References

1. D. W. Brown, "GT-2A Pumping Tests: A Lesson in History," G-3/78/#34, Dec. 14, 1978.
2. Z. Dash et al, "Hot Dry Rock Geothermal Reservoir Testing: 1978-1980," LA-9080-SR, Nov. 1981.
3. G. A. Zyvoloski et al, "Evaluation of the Second Hot Dry Rock Geothermal Energy Reservoir: Results of Phase I, Run Segment 5," LA-8940-HDR, Sept. 1981.